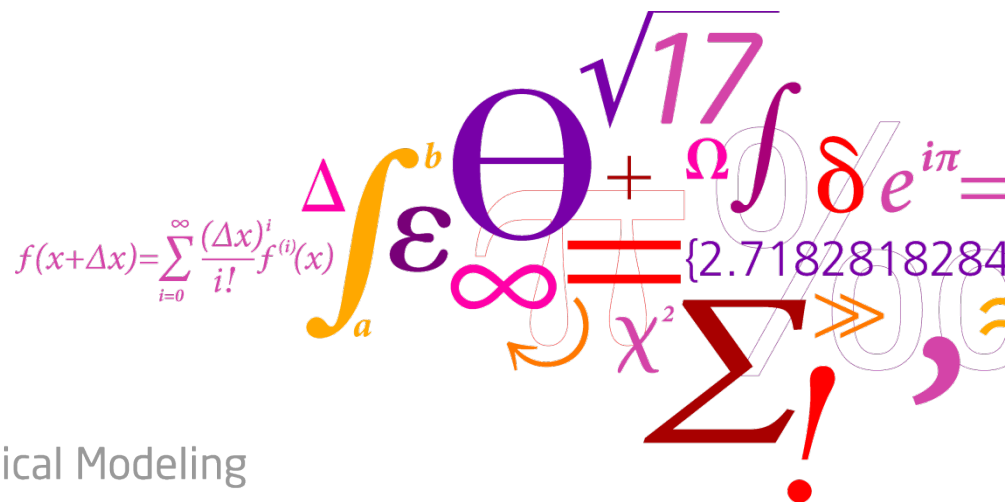


Tools for decision making under uncertainty in electricity markets

Lecture 3: “Market clearing under uncertainty”

Juan Miguel Morales
Salvador Pineda

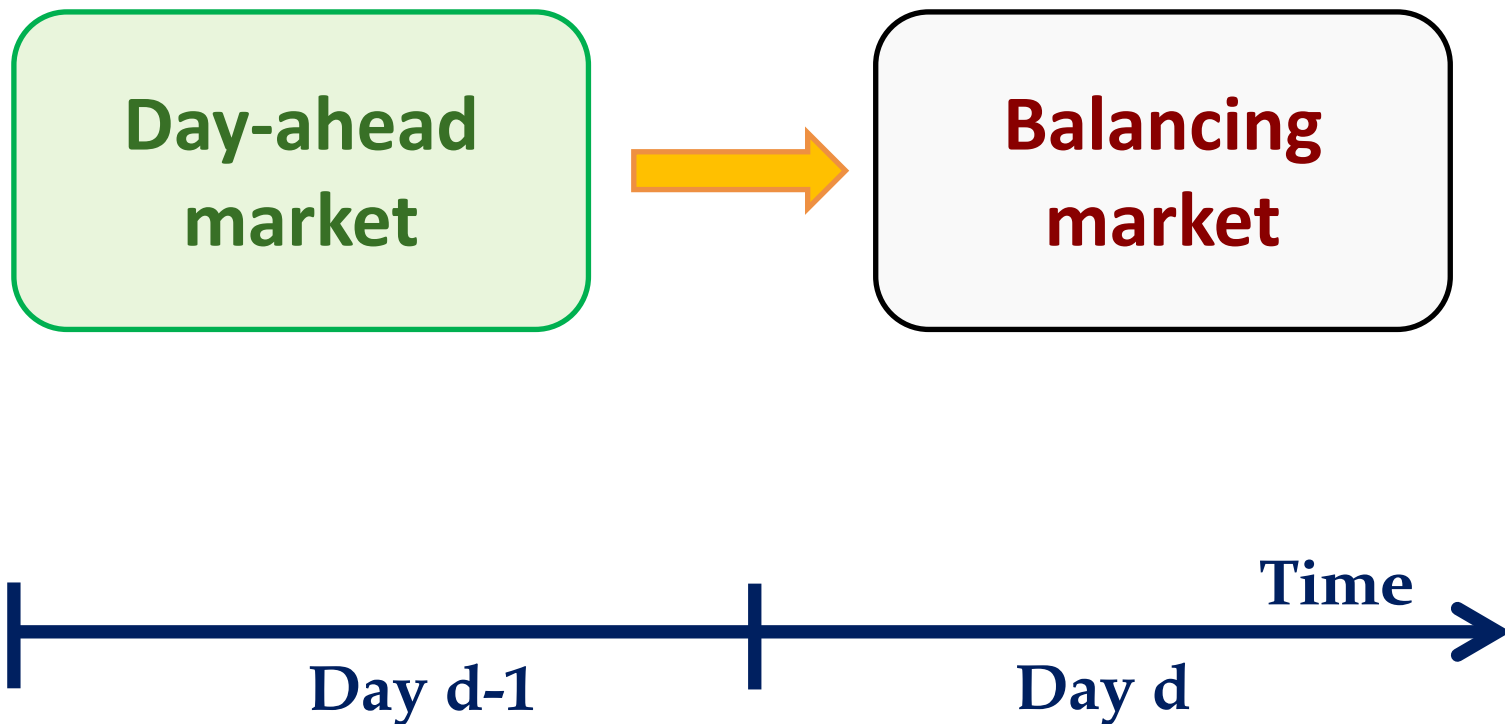


Outline

- 1) Spot electricity markets
- 2) Market-clearing procedures
- 3) Energy and reserve capacity
- 4) Stochastic market clearing

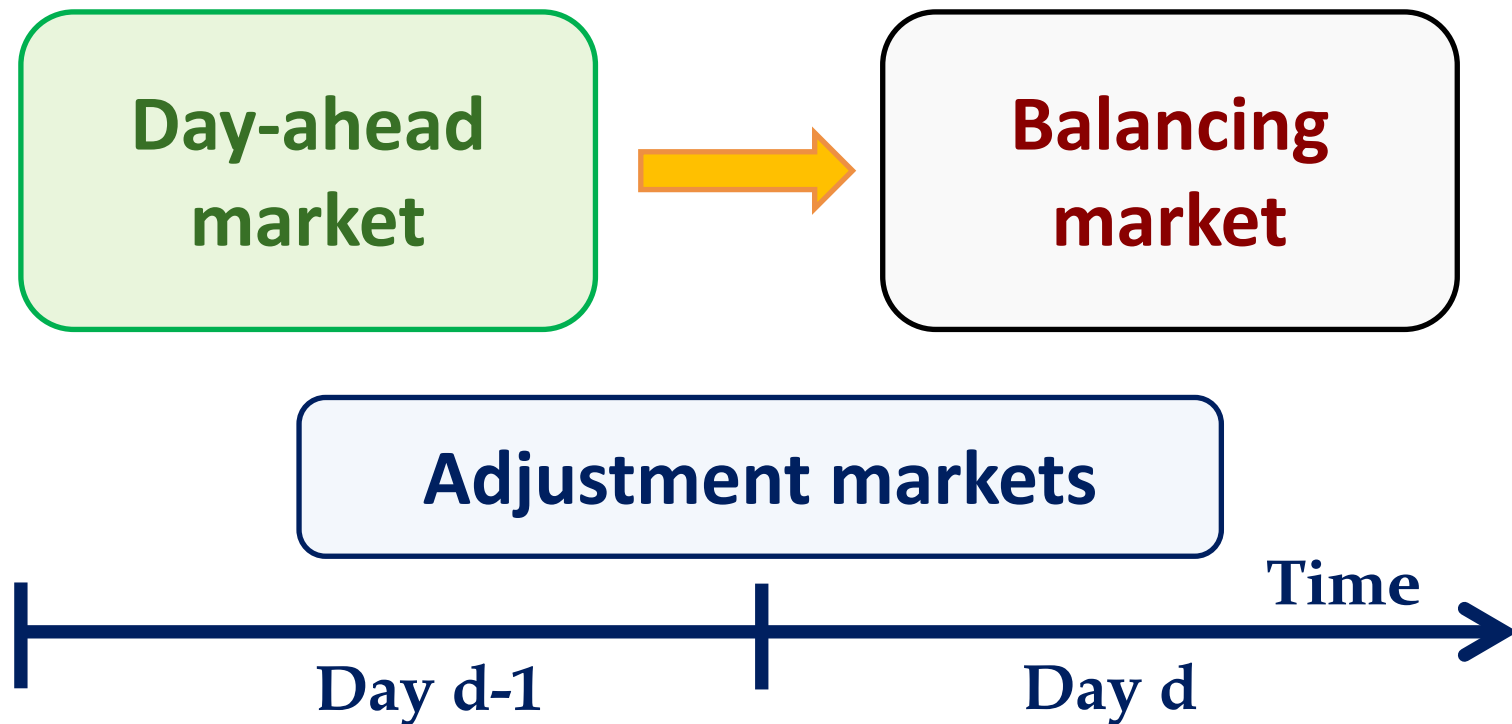
Spot electricity markets

(Basic structure)



Spot electricity markets

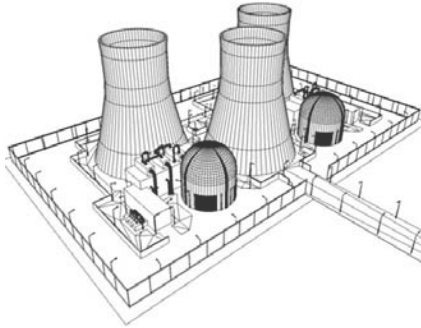
(Basic structure)



Spot electricity markets

(Conventional vs. stochastic)

**Day-ahead
market**



**Inflexible units
(need advance planning)**

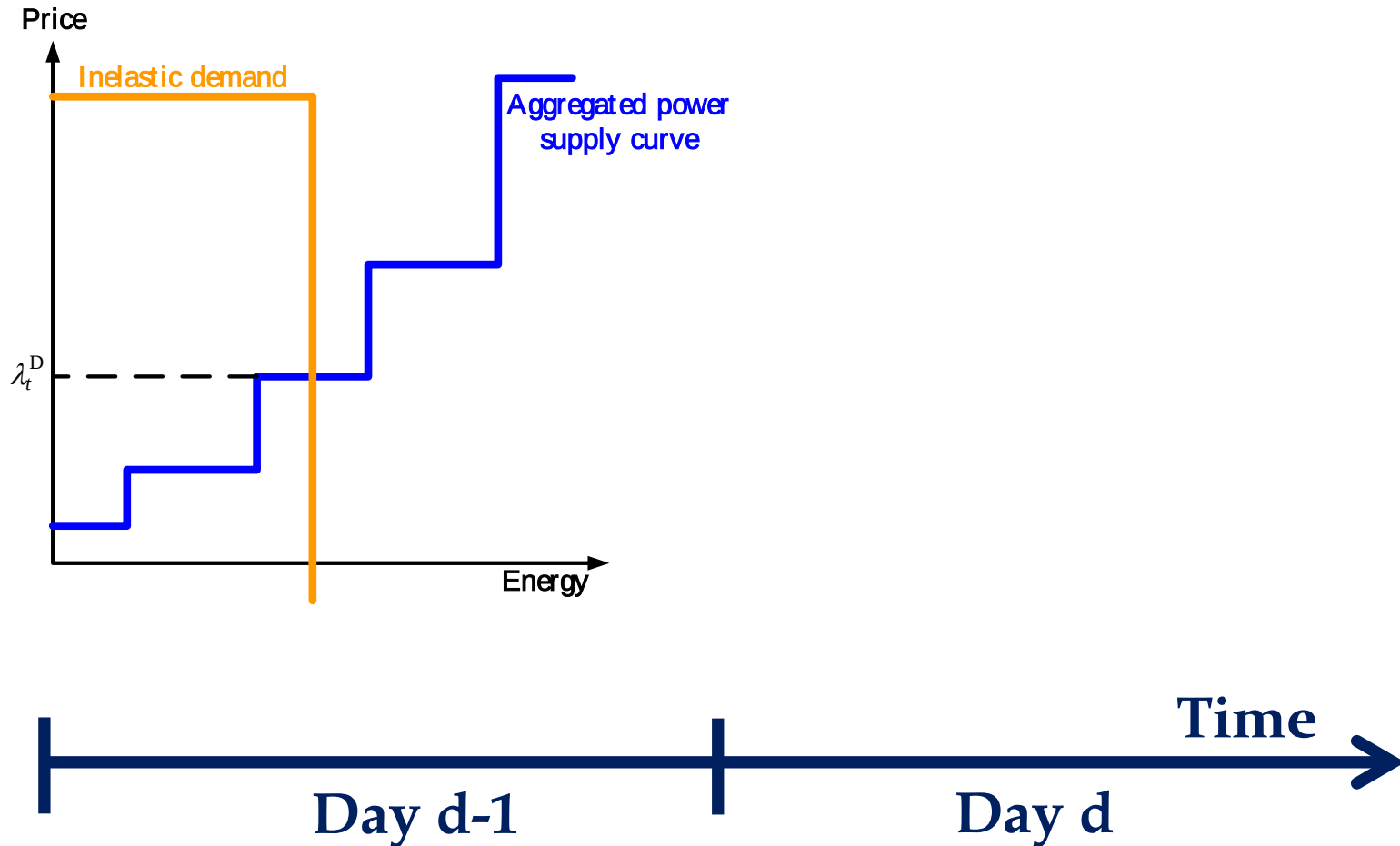


**Balancing
market**

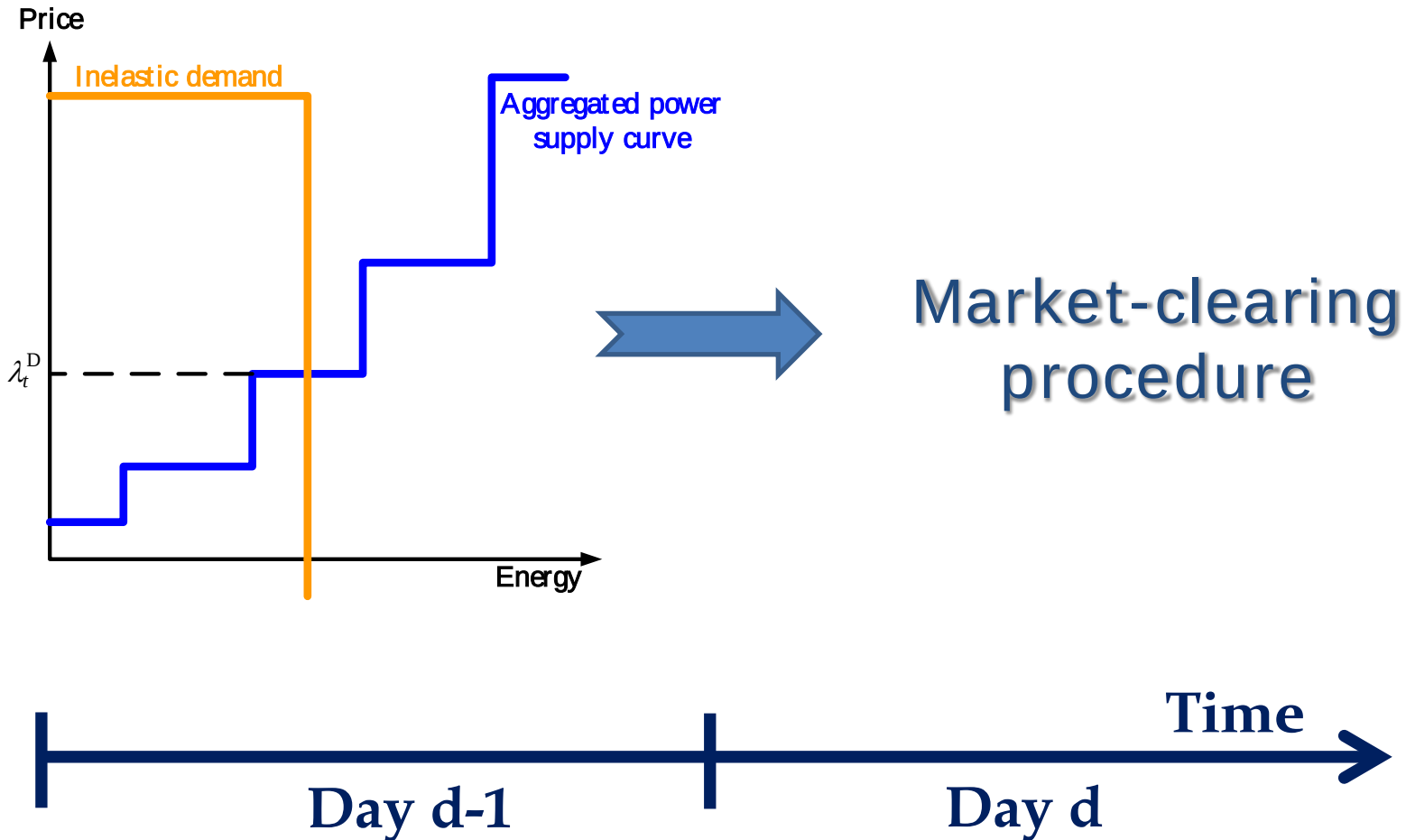


**Wind producers/consumers
(need balancing energy)**

Spot electricity markets (Pool)



Spot electricity markets (Pool)



Market clearing (Procedures)

- **Single-period auction:**

- Social welfare maximization/Production cost minimization
- Energy offers from producers $\Rightarrow$ (quantity, selling price)
- Energy bids from consumers $\Rightarrow$ (quantity, purchase price)
- Production limits (minimum/maximum)
- A market-clearing price (MCP)

- **Multi-period auction:**

- + Inter-temporal constraints: Ramping limits and minimum up/down times
- A series of MCPs

Market clearing (Procedures)

- **Network-constrained auction:**

- + Network constraints: Transmission capacity limits, reference node, ...
- Locational marginal prices (LMPs)
- AC-OPF/DC-OPF
- Single-period/Multi-period

- **Walrasian auction:**

1. Price broadcast
2. Self-dispatch of market participants
3. Imbalance determination (demand minus production)
4. If the imbalance is small enough, stop; if not, prices are modified proportionally to imbalance, and the process continues in step 2

Single-period auction

(Example)

Data

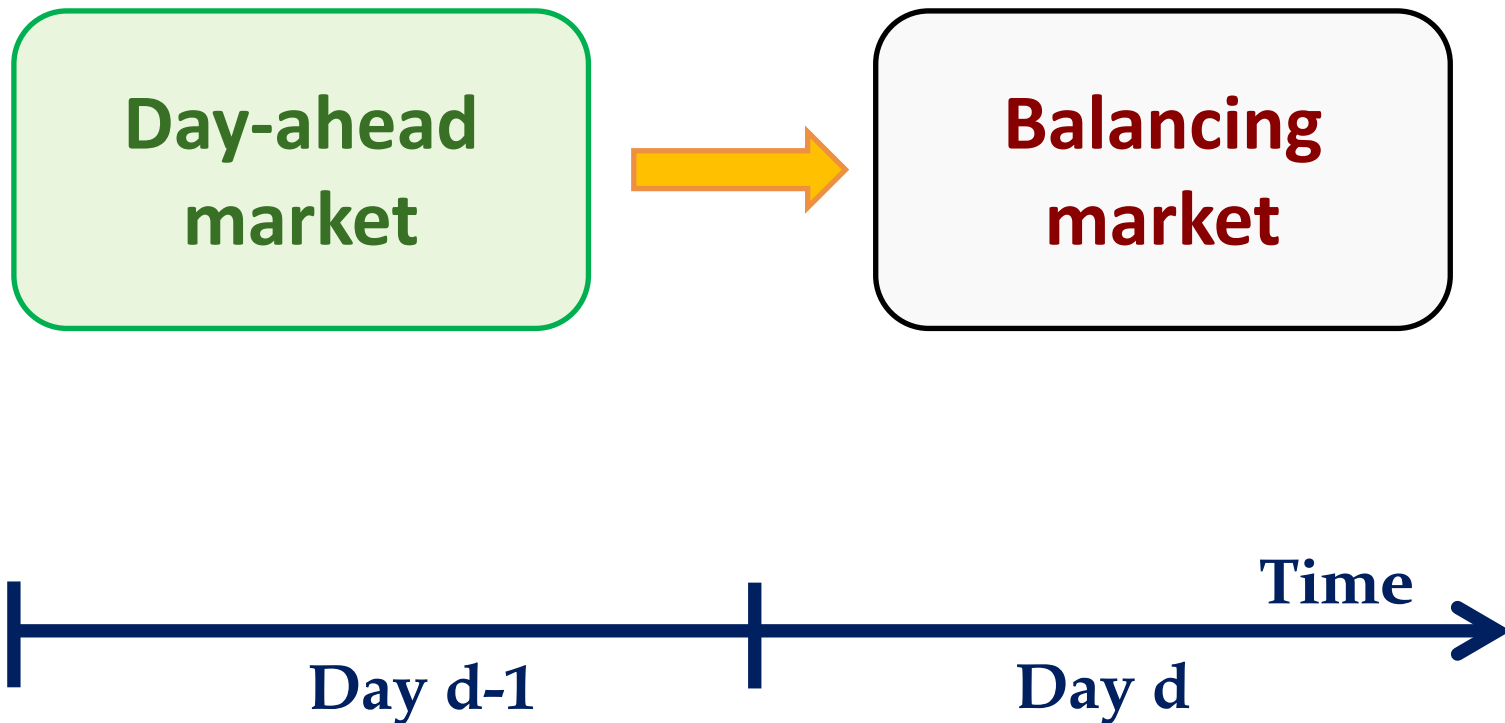
- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Demand: 130MW

Single-period auction (Example)

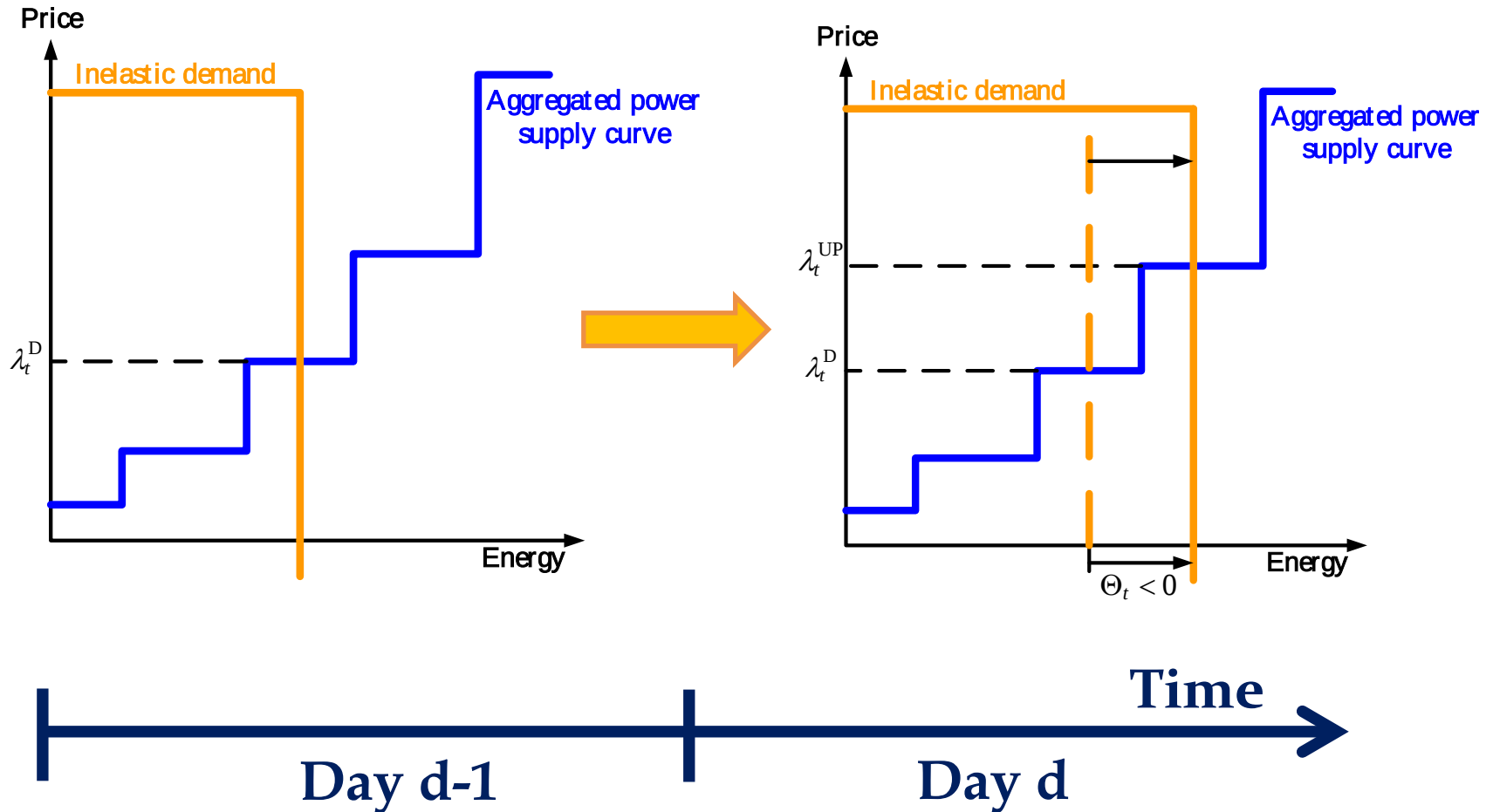
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Spot electricity markets

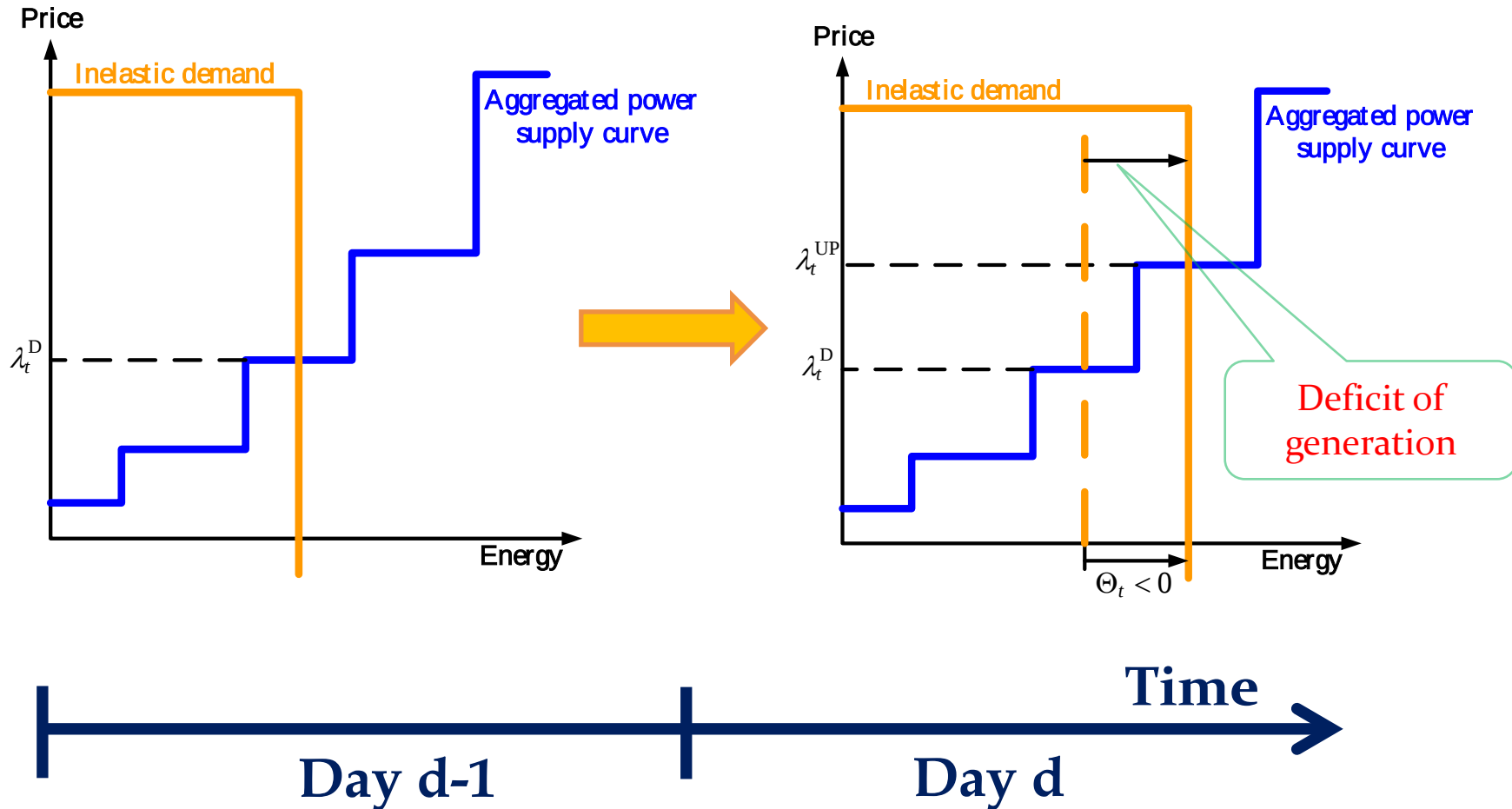
(Balancing market)



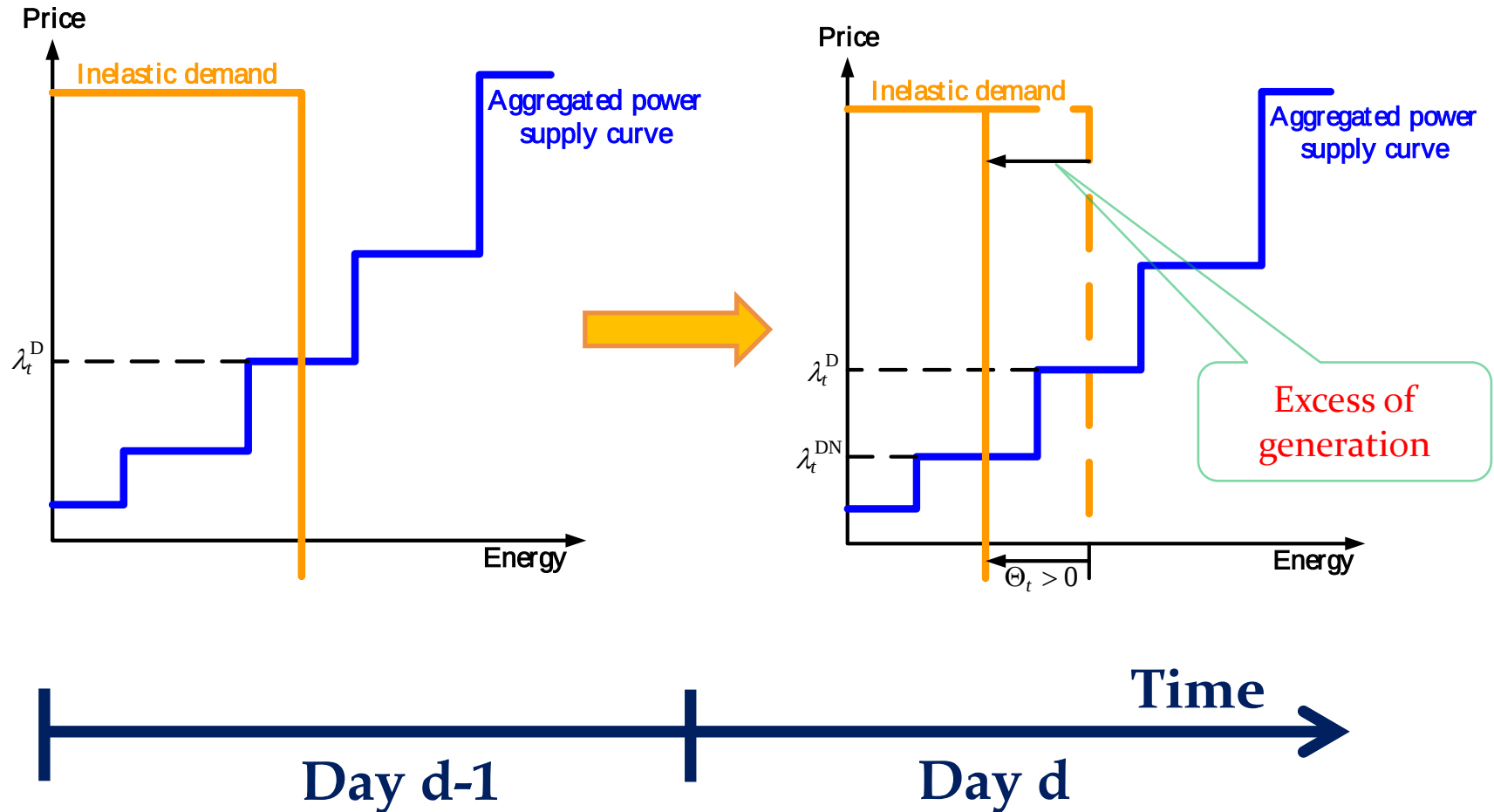
Spot electricity markets (Balancing market)



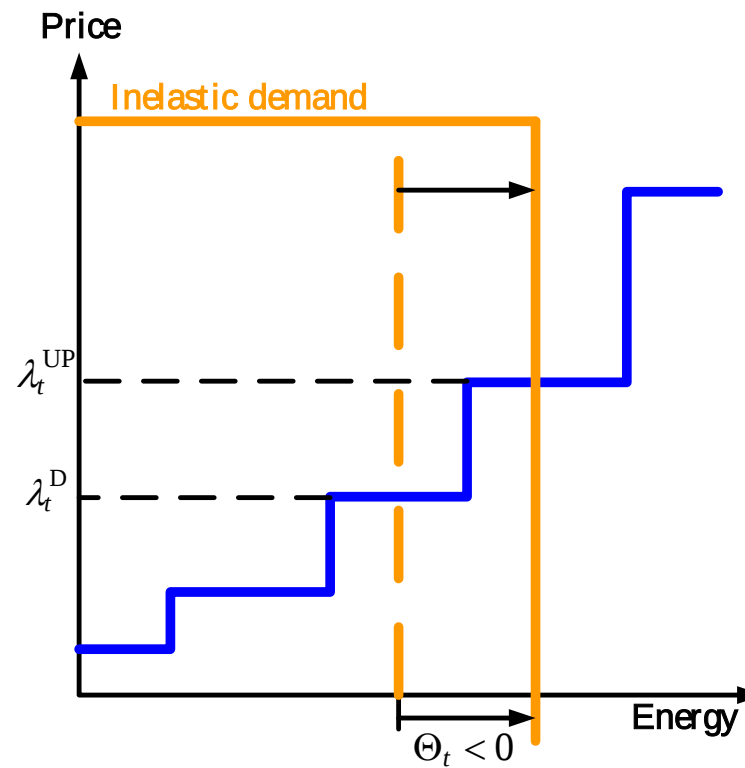
Spot electricity markets (Balancing market)



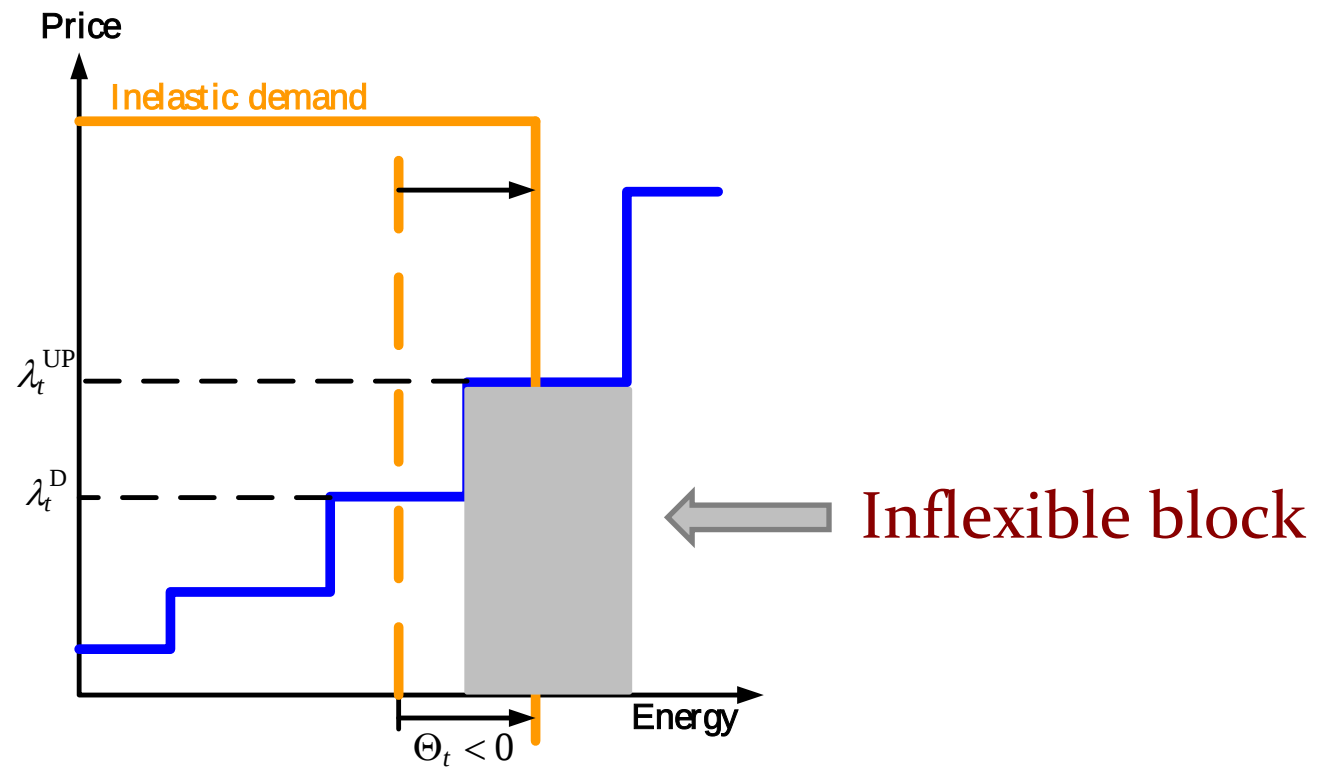
Spot electricity markets (Balancing market)



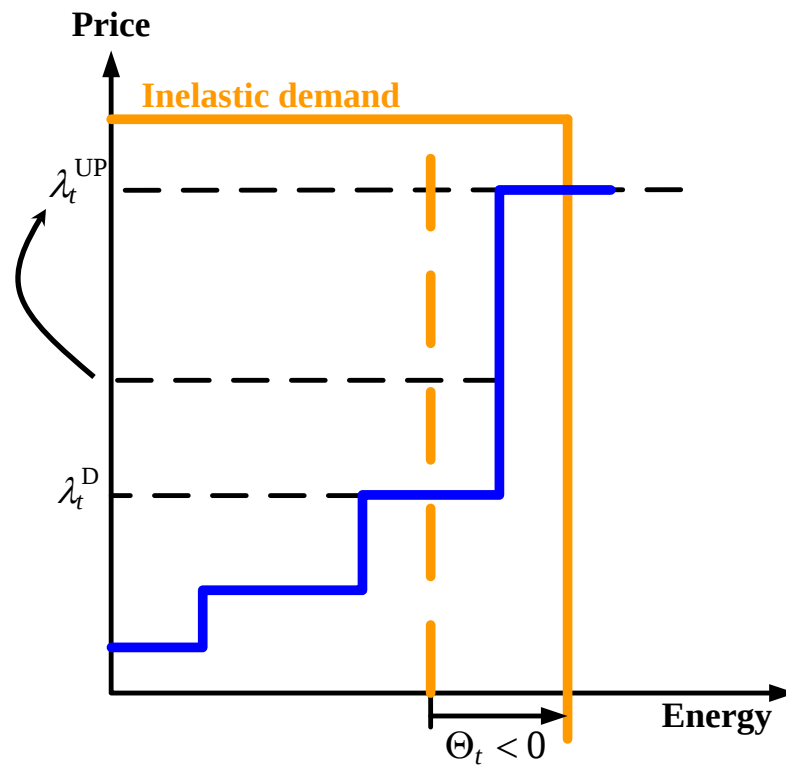
Balancing market (Stochastic producer)



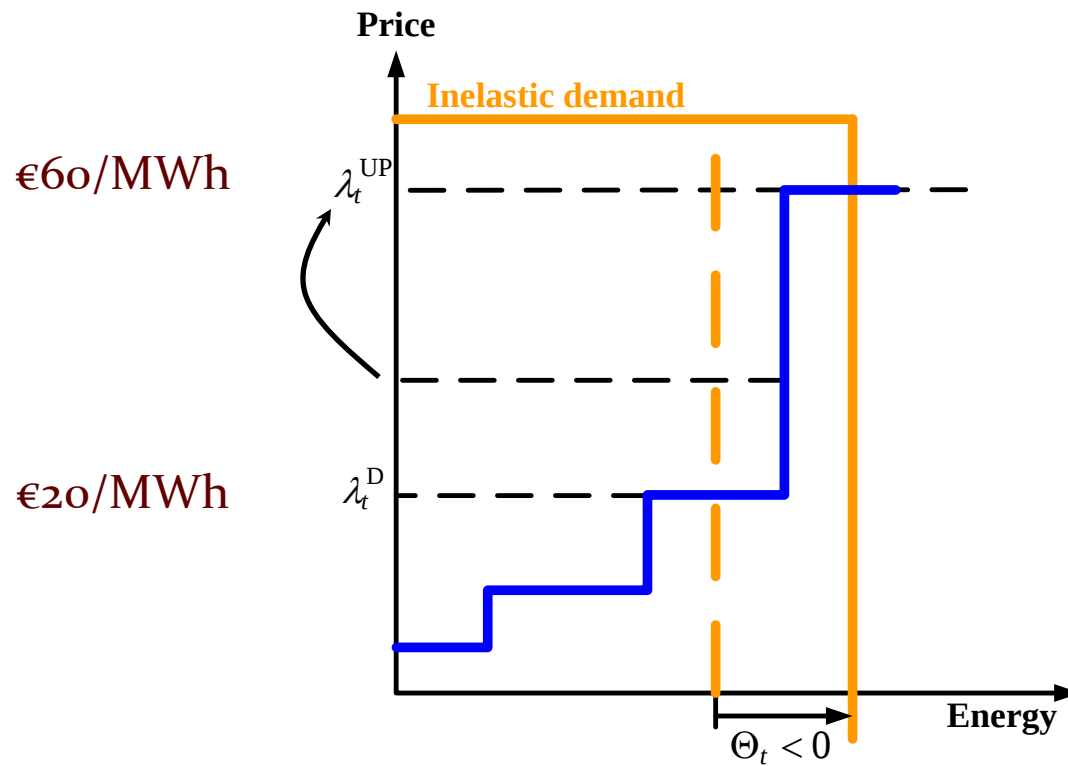
Balancing market (Stochastic producer)



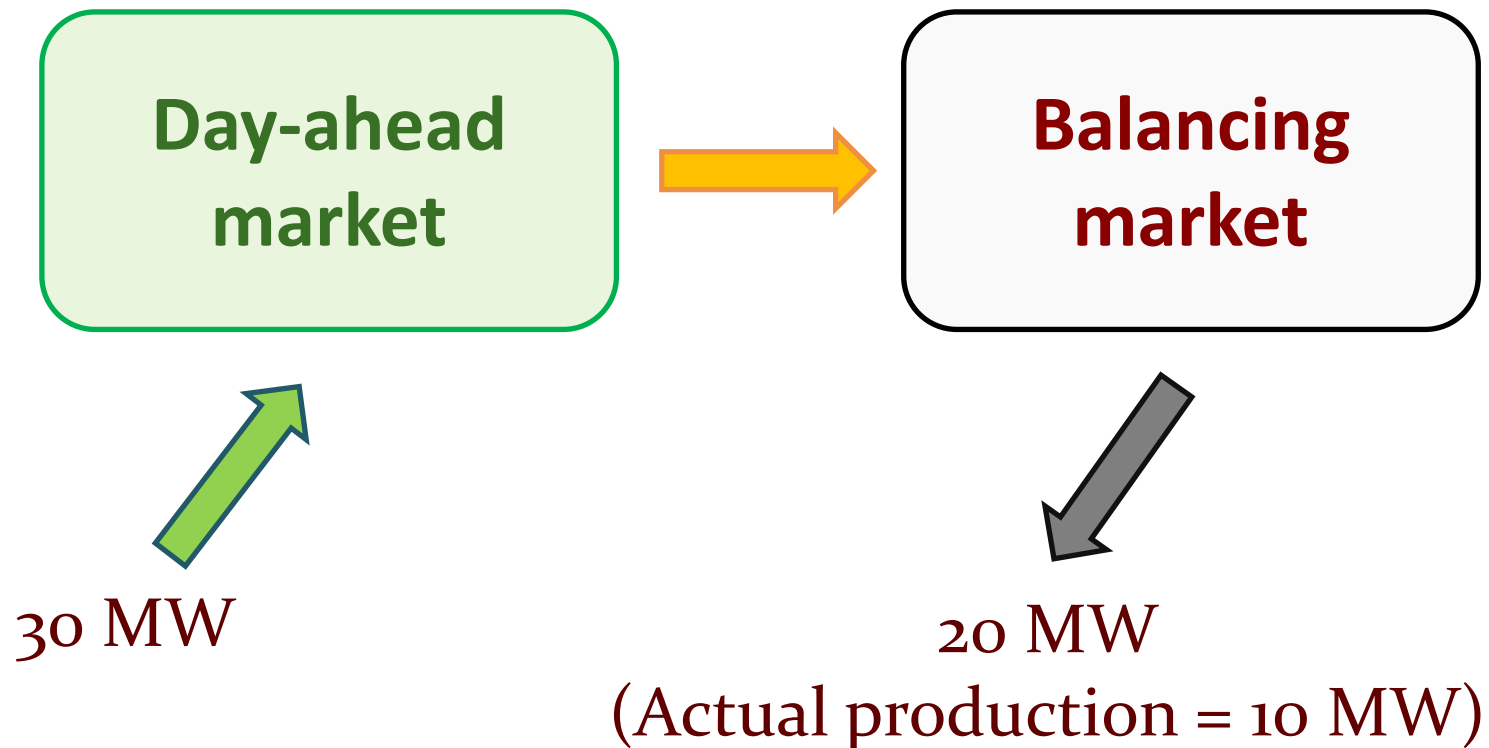
Balancing market (Stochastic producer)



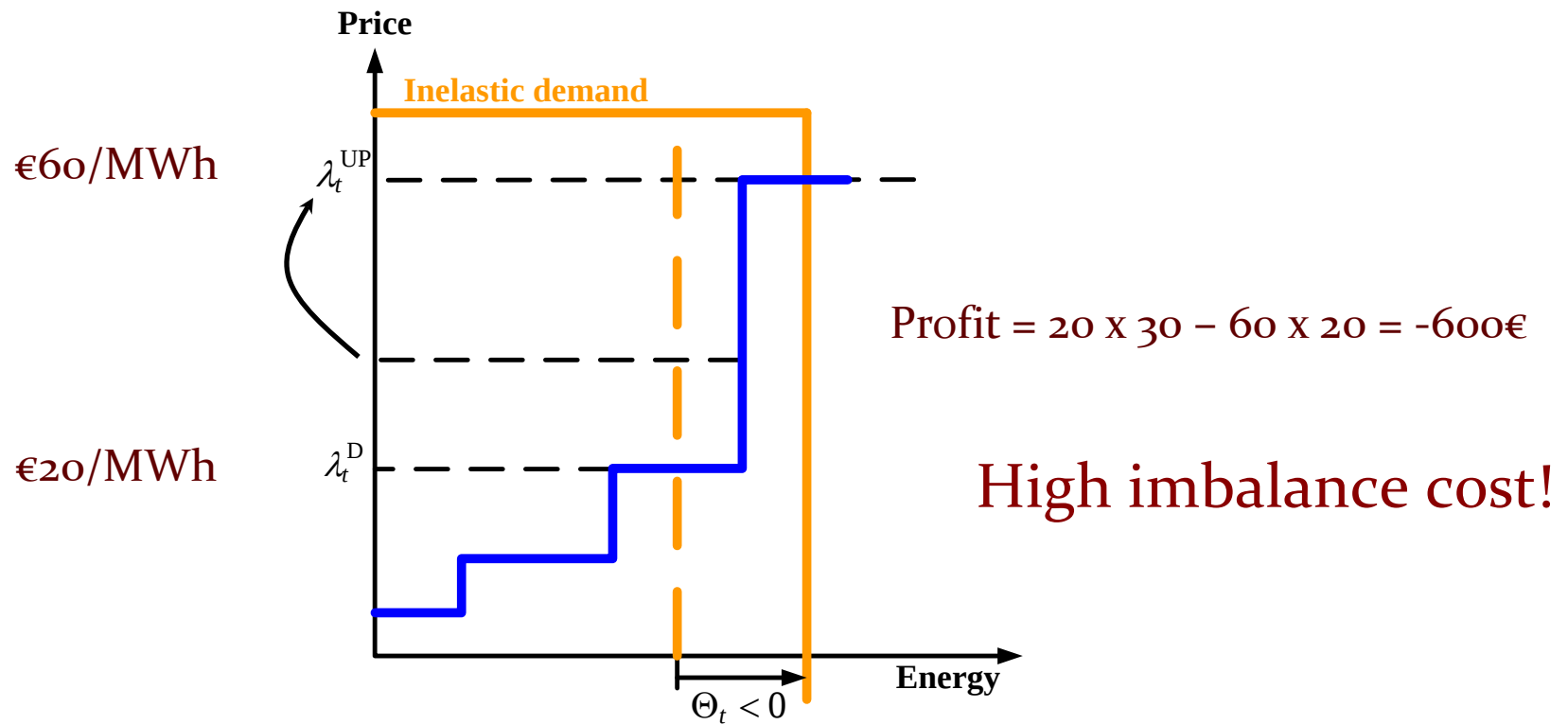
Balancing market (Stochastic producer)



Balancing market (Stochastic producer)

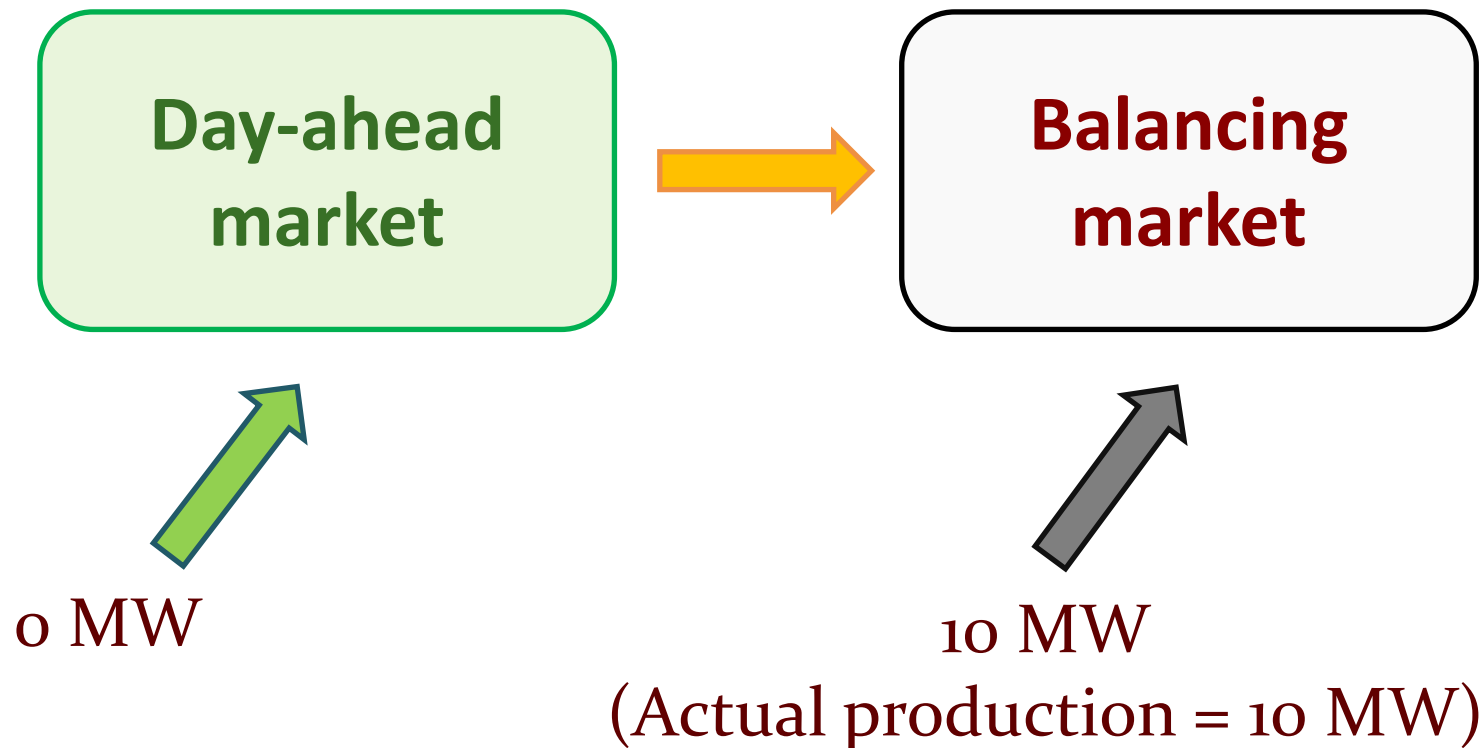


Balancing market (Stochastic producer)

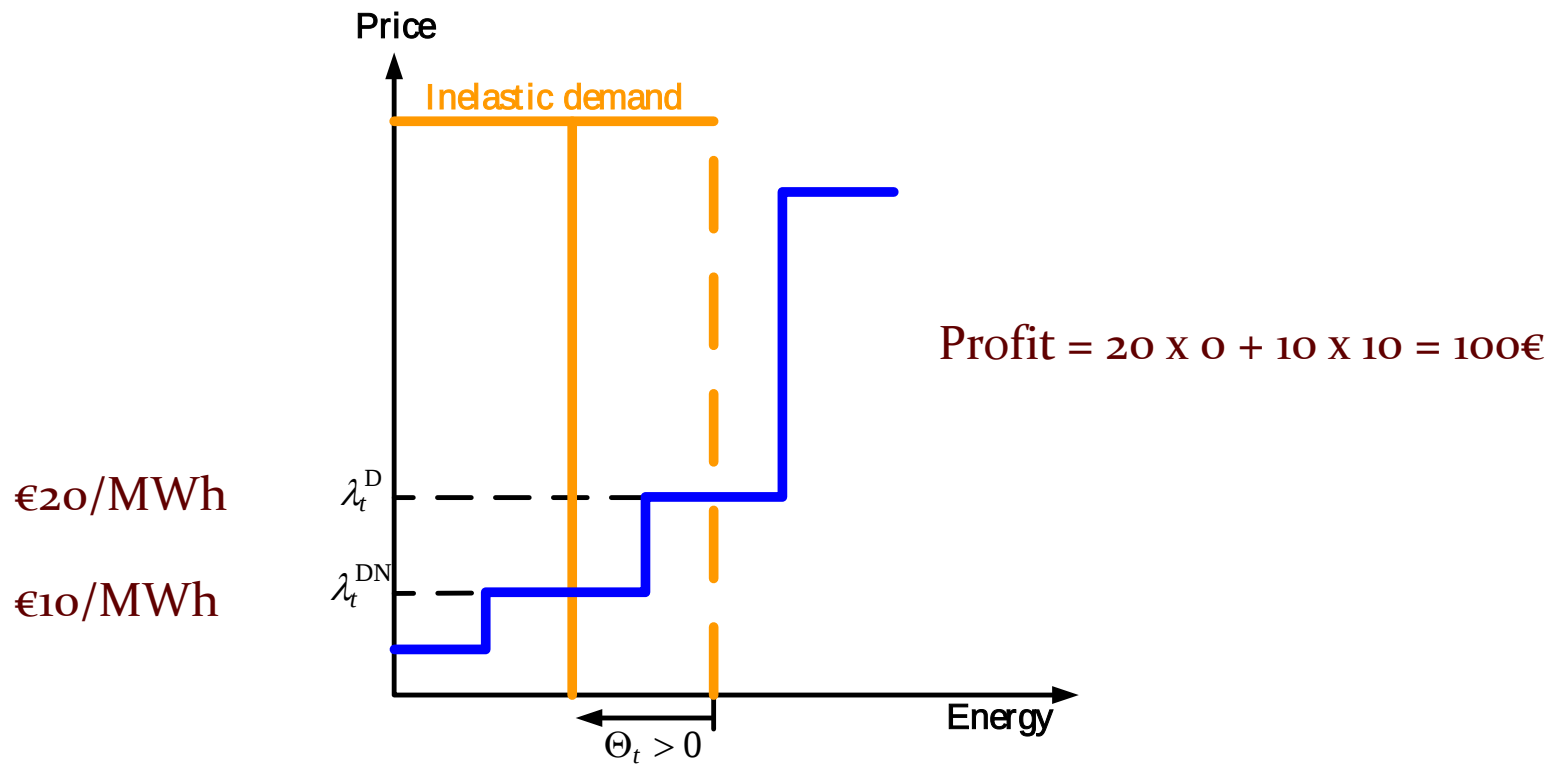


Balancing market

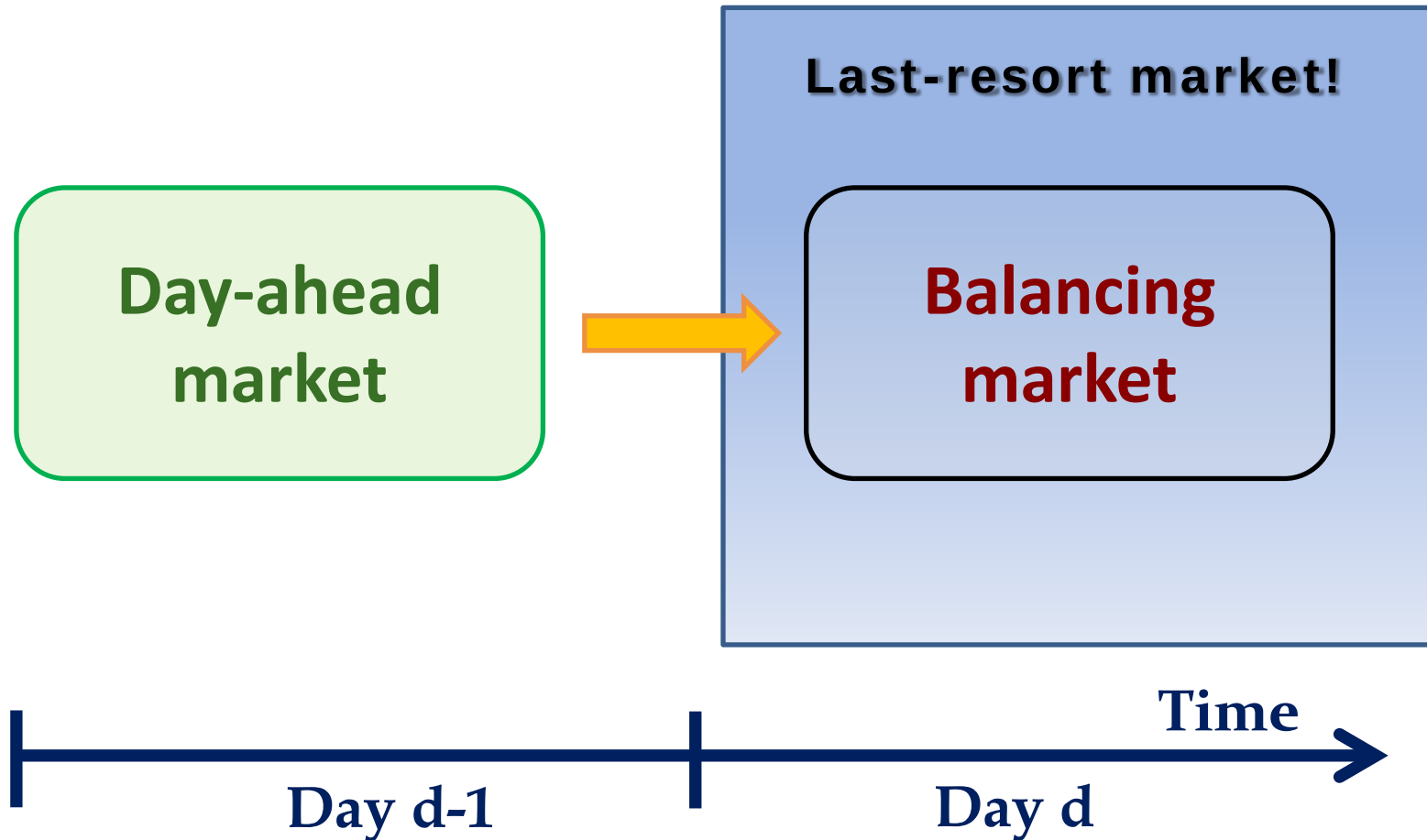
(Stochastic producer)



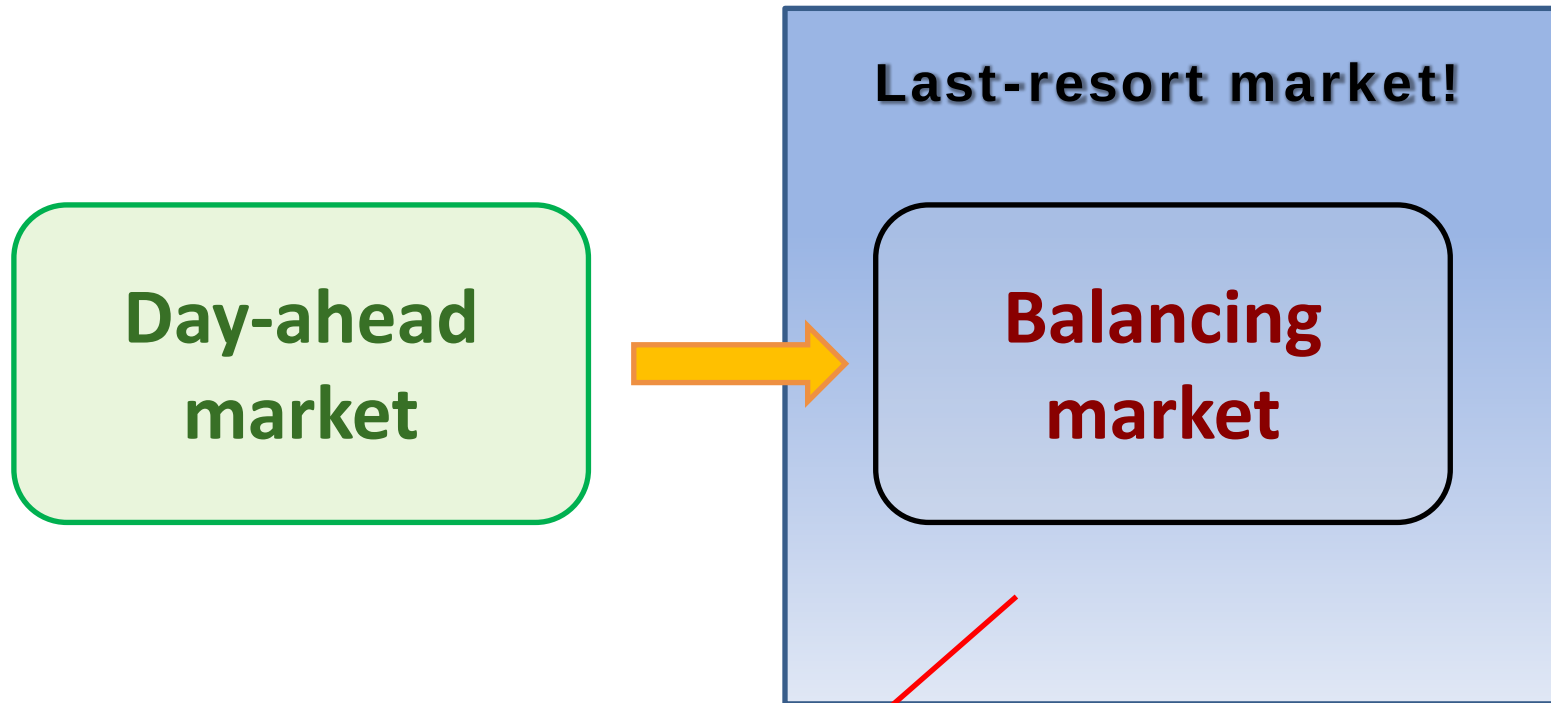
Balancing market (Stochastic producer)



Balancing market (Consumers)

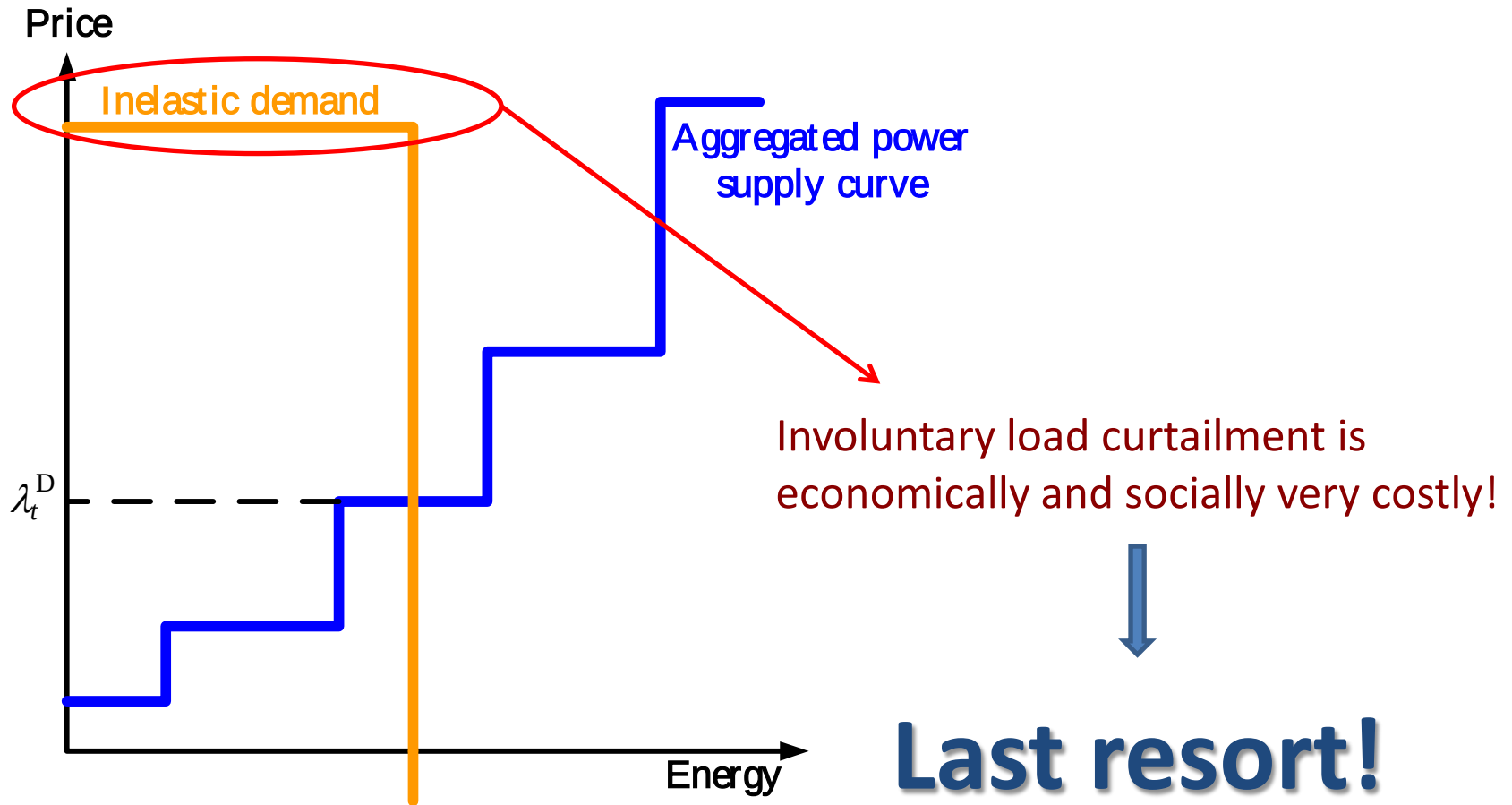


Balancing market (Consumers)

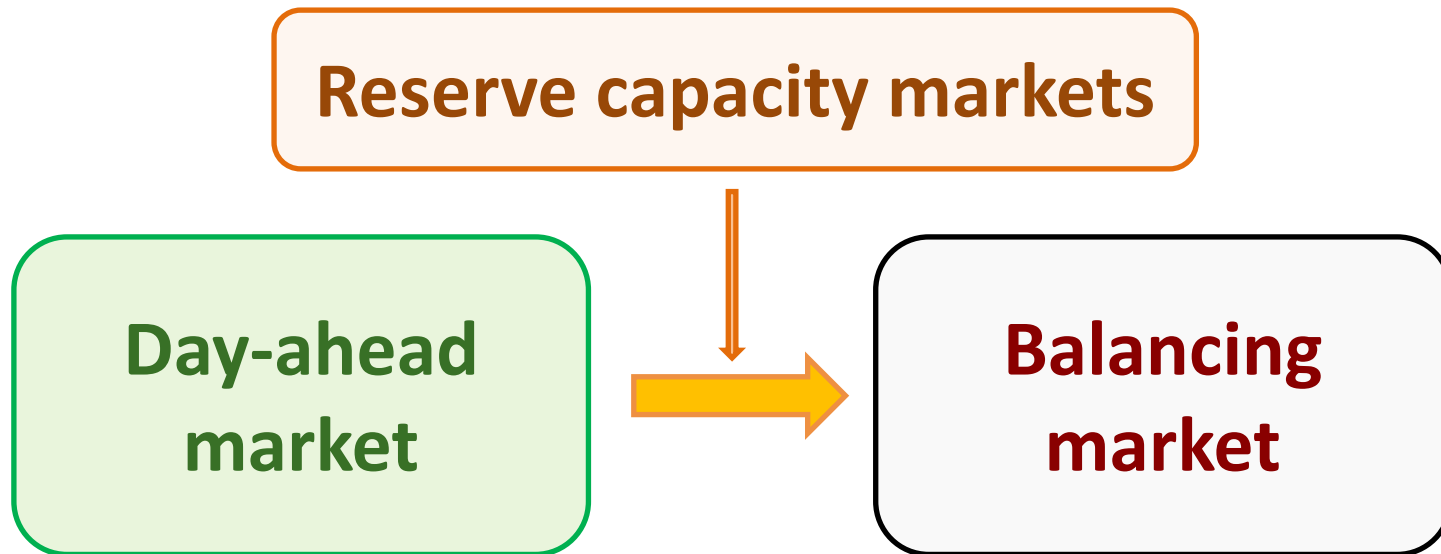


The balancing market reconciles economic efficiency and **security**

Balancing market (Consumers)



Reserve capacity markets (Motivation)



To guarantee enough balancing resources are available during the real-time operation of the power system

Reserve capacity markets

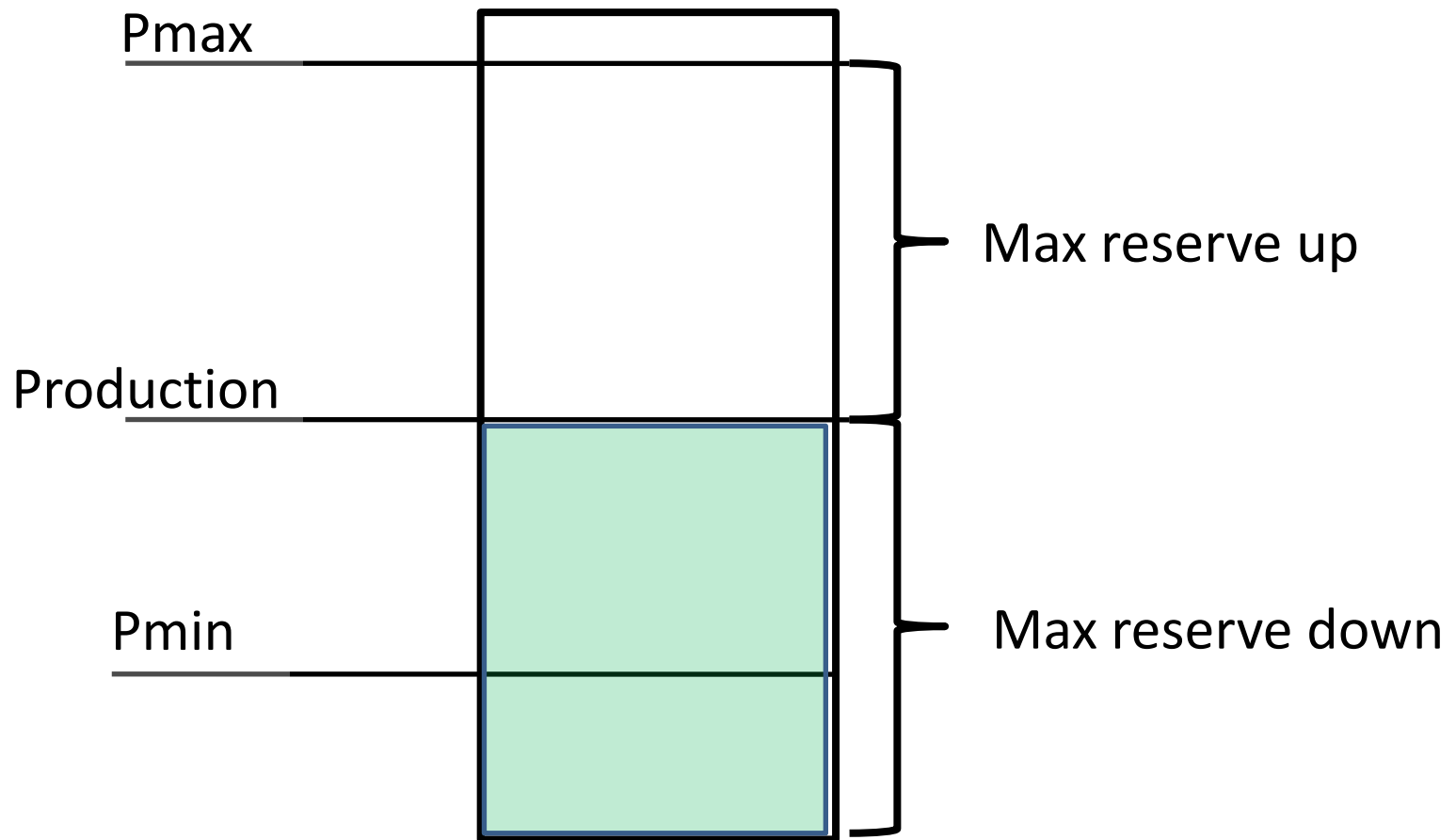
(Basic concepts)



- **Reserve capacity:** The capability of a power system above and below its current operating point to act in response of a disturbance within a specified time interval
- **Reserve deployment:** Collection of security corrective actions through which the reserve capacity is transformed into energy in the aftermath of a disturbance
- **Classification criteria:**
 - Spinning (synchronized)/non-spinning (not synchronized)
 - Activation time/purpose: Primary/Secondary/Tertiary
 - Purpose: contingency reserve/forecast errors/black-start
 - ...

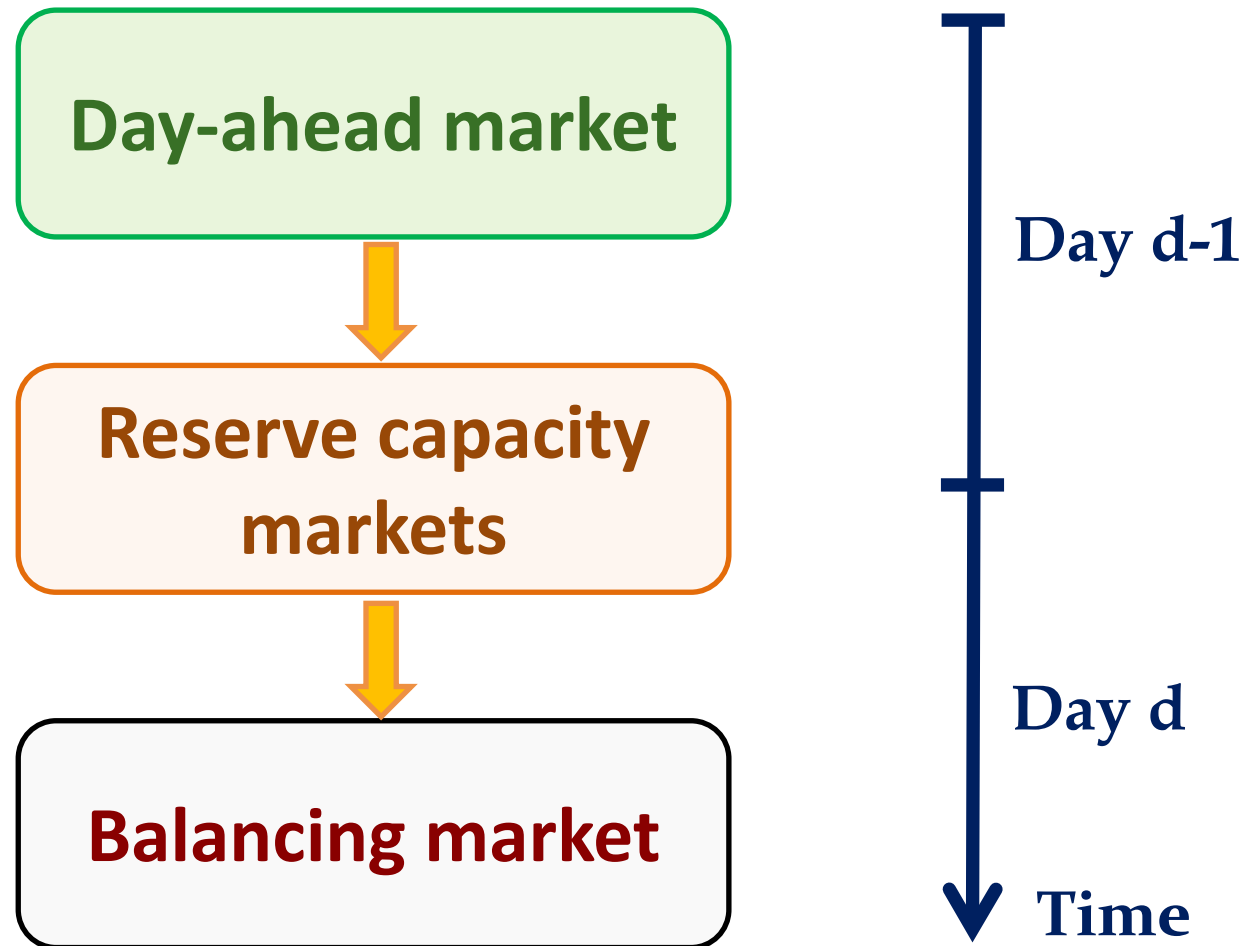
Reserve capacity markets

(Basic concepts)



Reserve capacity markets (Configurations)

**Sequential
set-up**



Reserve capacity markets

(Example: Sequential)



Data

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Demand: 130MW
- Reserve capacity requirement: 20MW
 - Producer A: free reserve capacity
 - Producer B: \$25/MW

Reserve capacity markets

(Example: Sequential)

Data

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Demand: 130MW
- Reserve capacity requirement: 20MW
 - Producer A: free reserve capacity
 - Producer B: \$25/MW

Reserve capacity markets

(Example: Sequential)

Energy dispatch

$$\begin{array}{l} \text{Min } 10P_A + 30P_B \\ \text{s.t.} \\ P_A + P_B = 130 \\ 0 \leq P_A \leq 100 \\ 0 \leq P_B \leq 100 \end{array} \quad \rightarrow \quad \begin{cases} P_A^* = 100 \text{ MW} \\ P_B^* = 30 \text{ MW} \\ \lambda_E^* = \$30 / \text{MWh} \end{cases}$$

Reserve capacity markets

(Example: Sequential)

Reserve dispatch

$$\begin{array}{l} \text{Min } 0R_A + 25R_B \\ \text{s.t.} \\ R_A + R_B = 20 \\ 0 \leq R_A \leq 100 - P_A^* \\ 0 \leq R_B \leq 100 - P_B^* \end{array} \quad \longrightarrow \quad \begin{cases} R_A^* = 0 \text{ MW} \\ R_B^* = 20 \text{ MW} \\ \lambda_R^* = \$25 / \text{MW} \end{cases}$$

Reserve capacity markets

(Example: Sequential)

Reserve dispatch

$$\begin{array}{l} \text{Min } 0R_A + 25R_B \\ \text{s.t.} \\ R_A + R_B = 20 \\ 0 \leq R_A \leq 100 - P_A^* \\ 0 \leq R_B \leq 100 - P_B^* \end{array} \quad \xrightarrow{\quad} \quad \begin{cases} R_A^* = 0 \text{ MW} \\ R_B^* = 20 \text{ MW} \\ \lambda_R^* = \$25 / \text{MW} \end{cases}$$

Inputs!

Reserve capacity markets

(Example: Sequential)

$$P_A^* = 100\text{MW} \quad P_B^* = 30\text{MW} \quad \lambda_E^* = \$30 / \text{MWh}$$

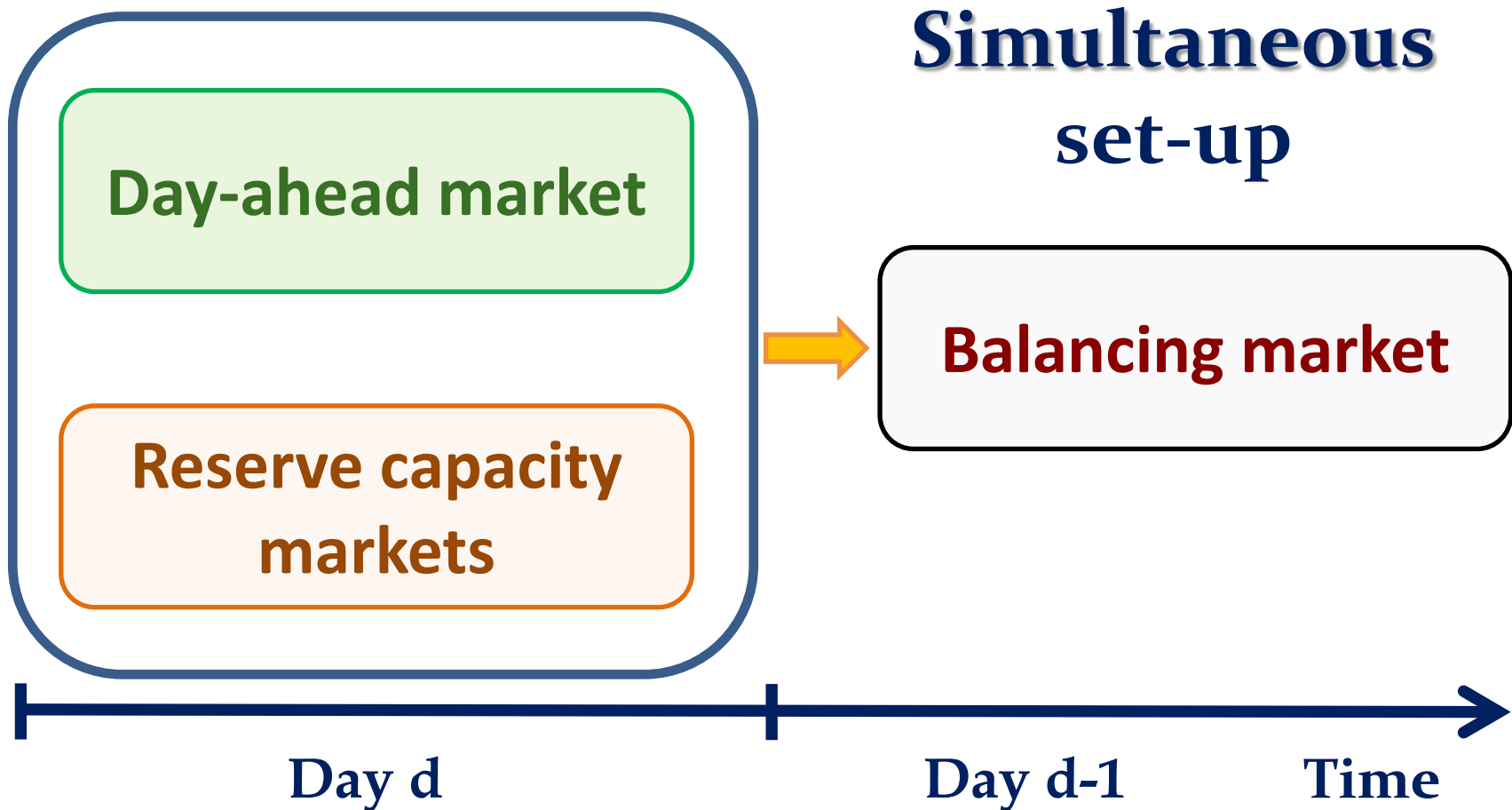
$$R_A^* = 0\text{MW} \quad R_B^* = 20\text{MW} \quad \lambda_R^* = \$25 / \text{MW}$$

$$\begin{aligned} \text{TC}^{\text{seq}} &= 10P_A^* + 30P_B^* + 0R_A^* + 25R_B^* = \\ &= 10 \cdot 100 + 30 \cdot 30 + 0 + 25 \cdot 20 = \$2400 \end{aligned}$$

$$\text{profit}_A^{\text{seq}} = (30 - 10)P_A^* + (25 - 0)R_A^* = \$2000$$

$$\text{profit}_B^{\text{seq}} = (30 - 30)P_B^* + (25 - 25)R_B^* = \$0$$

Reserve capacity markets (Configurations)



Reserve capacity markets

(Example: Simultaneous)



Data

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Demand: 130MW
- Reserve capacity requirement: 20MW
 - Producer A: free reserve capacity
 - Producer B: \$25/MW

Reserve capacity markets

(Example: Simultaneous)

$$\begin{array}{ll} \text{Min } 10P_A + 30P_B + & \\ & + 0R_A + 25R_B \\ \text{s.t.} & \\ P_A + P_B = 130 & \\ R_A + R_B = 20 & \\ P_A + R_A \leq 100 & \\ P_B + R_B \leq 100 & \\ P_A \geq 0 \quad P_B \geq 0 & \\ R_A \geq 0 \quad R_B \geq 0 & \end{array} \quad \Rightarrow \quad \begin{array}{l} P_A^* = 80\text{MW} \\ R_A^* = 20\text{MW} \\ P_B^* = 50\text{MW} \\ R_B^* = 0\text{MW} \\ \lambda_E^* = \$30 / \text{MWh} \\ \lambda_R^* = \$20 / \text{MWh} \end{array}$$

Reserve capacity markets

(Example: Simultaneous)

$$P_A^* = 80\text{MW} \quad P_B^* = 50\text{MW} \quad \lambda_E^* = \$30 / \text{MWh}$$

$$R_A^* = 20\text{MW} \quad R_B^* = 0\text{MW} \quad \lambda_R^* = \$20 / \text{MW}$$

$$\begin{aligned} \text{TC}^{\text{sim}} &= 10P_A^* + 30P_B^* + 0R_A^* + 25R_B^* = \\ &= 10 \cdot 80 + 30 \cdot 50 + 0 \cdot 20 + 25 \cdot 0 = \$2300 \end{aligned}$$

$$\text{profit}_A^{\text{sim}} = (30 - 10)P_A^* + (20 - 0)R_A^* = \$2000$$

$$\text{profit}_B^{\text{sim}} = (30 - 30)P_B^* + (20 - 25)R_B^* = \$0$$

Reserve capacity markets

(Example: Comparison)

	Sequential		Simultaneous	
	Prod A	Prod B	Prod A	Prod B
Power	100MW	30MW	80MW	50MW
Reserve	0MW	20MW	20MW	0MW

	Sequential	Simultaneous
Energy price	\$30/MWh	\$30/MWh
Reserve price	\$25/MWh	\$20/MWh
Total Cost	\$2400	\$2300
Profit A	\$2000	\$2000
Profit B	\$0	\$0

Reserve capacity markets

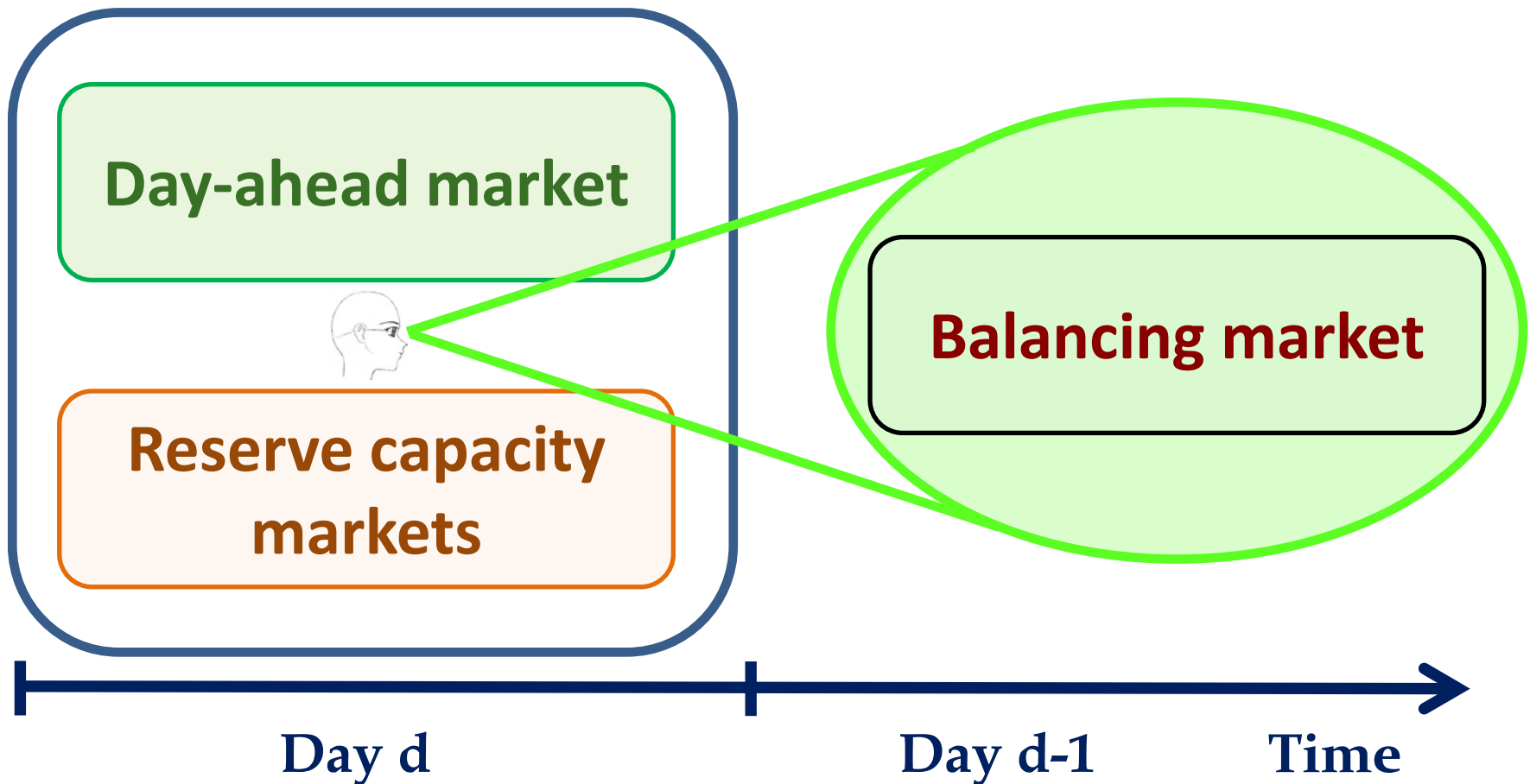
(Example: Comparison)

	Sequential		Simultaneous	
	Prod A	Prod B	Prod A	Prod B
Power	100MW	30MW	80MW	50MW
Reserve	0MW	20MW	20MW	0MW

	Sequential	Simultaneous
Energy price	\$30/MWh	\$30/MWh
Reserve price	\$25/MWh	\$20/MWh
Total Cost	\$2400	\$2300
Profit A	\$2000	\$2000
Profit B	\$0	\$0

Stochastic market-clearing

(Basic idea)



Stochastic market-clearing

(Basic idea)



- Energy and reserve dispatches anticipate plausible balancing market outcomes
- The anticipation is based on a probabilistic description of uncertain factors
- Reserve requirements are *endogenously* estimated using a stochastic security metric: The expected load not served (ELNS)
- The cost of security is driven by the ELNS
- Maximization of the *expected* social welfare

Stochastic market-clearing (Example)



Data

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Demand: 130MW
- Reserve capacity requirement: 20MW
 - Producer A: free reserve capacity
 - Producer B: \$25/MW

Stochastic market-clearing (Example)

Data

- Producer A: 100MW & \$10/MWh
- Producer B: 100MW & \$30/MWh
- Demand: 130MW  May unexpectedly increase up to 150 MW with a probability of 0.05
- Reserve capacity requirement: 20MW
 - Producer A: free reserve capacity
 - Producer B: \$25/MW

Stochastic market-clearing (Example)



Three types of balancing actions ...

1. Producer A may increase its production from P_A to $P_A + r_A$ with $r_A \leq R_A$
2. Producer B may increase its production from P_B to $P_B + r_B$ with $r_B \leq R_B$
3. A part of the load increase, L^{shed} , may be simply not supplied at a cost of \$1000/MWh

Stochastic market-clearing

(Example)

$$\begin{array}{l}
 \text{Min } 10P_A + 30P_B + \\
 \quad + 0R_A + 25R_B \\
 \quad + 0.05(10r_A + 30r_B + 1000L^{\text{shed}}) \\
 \text{s.t.} \\
 P_A + P_B = 130 \\
 r_A + r_B + L^{\text{shed}} = 20 \\
 P_A + R_A \leq 100 \\
 P_B + R_B \leq 100 \\
 r_A \leq R_A, \quad r_B \leq R_B \\
 P_A, P_B, R_A, R_B, r_A, r_B, L^{\text{shed}} \geq 0
 \end{array}
 \quad \Rightarrow \quad
 \begin{array}{l}
 P_A^* = 80\text{MW} \\
 R_A^* = 20\text{MW} \\
 P_B^* = 50\text{MW} \\
 R_B^* = 0\text{MW} \\
 r_A^* = 20\text{MW} \\
 r_B^* = 0 \\
 L^{\text{shed}} = 0
 \end{array}$$

Stochastic market-clearing

(Example)

Expected cost at the balancing stage

$$\begin{aligned}
 & \text{Min } 10P_A + 30P_B + \\
 & \quad + 0R_A + 25R_B \\
 & \quad + 0.05(10r_A + 30r_B + 1000L^{\text{shed}})
 \end{aligned}$$

s.t.

$$\begin{aligned}
 & P_A + P_B = 130 \\
 & r_A + r_B + L^{\text{shed}} = 20 \\
 & P_A + R_A \leq 100 \\
 & P_B + R_B \leq 100 \\
 & r_A \leq R_A, \quad r_B \leq R_B \\
 & P_A, P_B, R_A, R_B, r_A, r_B, L^{\text{shed}} \geq 0
 \end{aligned}$$

→

$$\begin{aligned}
 & P_A^* = 80\text{MW} \\
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 & R_B^* = 0\text{MW} \\
 & r_A^* = 20\text{MW} \\
 & r_B^* = 0 \\
 & L^{\text{shed}} = 0
 \end{aligned}$$

Stochastic market-clearing

(Example)

Min $10P_A + 30P_B +$
 $+ 0R_A + 25R_B$
 $+ 0.05(10r_A + 30r_B + 1000L^{\text{shed}})$

s.t.

$$P_A + P_B = 130$$

$$r_A + r_B + L^{\text{shed}} = 20$$

$$P_A + R_A \leq 100$$

$$P_B + R_B \leq 100$$

$$r_A \leq R_A, \quad r_B \leq R_B$$

$$P_A, P_B, R_A, R_B, r_A, r_B, L^{\text{shed}} \geq 0$$

Cost of the expected load not served

→

$$P_A^* = 80\text{MW}$$

$$R_A^* = 20\text{MW}$$

$$P_B^* = 50\text{MW}$$

$$R_B^* = 0\text{MW}$$

$$r_A^* = 20\text{MW}$$

$$r_B^* = 0$$

$$L^{\text{shed}} = 0$$

Stochastic market-clearing

(Example)

$$\begin{array}{l}
 \text{Min } 10P_A + 30P_B + \\
 \quad + 0R_A + 25R_B \\
 \quad + 0.05(10r_A + 30r_B + 1000L^{\text{shed}}) \\
 \text{s.t.} \\
 P_A + P_B = 130 \\
 r_A + r_B + L^{\text{shed}} = 20 \\
 P_A + R_A \leq 100 \\
 P_B + R_B \leq 100 \\
 r_A \leq R_A, \quad r_B \leq R_B \\
 P_A, P_B, R_A, R_B, r_A, r_B, L^{\text{shed}} \geq 0
 \end{array}
 \quad \Rightarrow \quad
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 P_A^* = 80\text{MW} \\
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 R_B^* = 0\text{MW} \\
 r_A^* = 20\text{MW} \\
 r_B^* = 0 \\
 L^{\text{shed}} = 0
 \end{array}$$

No reserve determination constraint

Stochastic market-clearing

(Exercise)



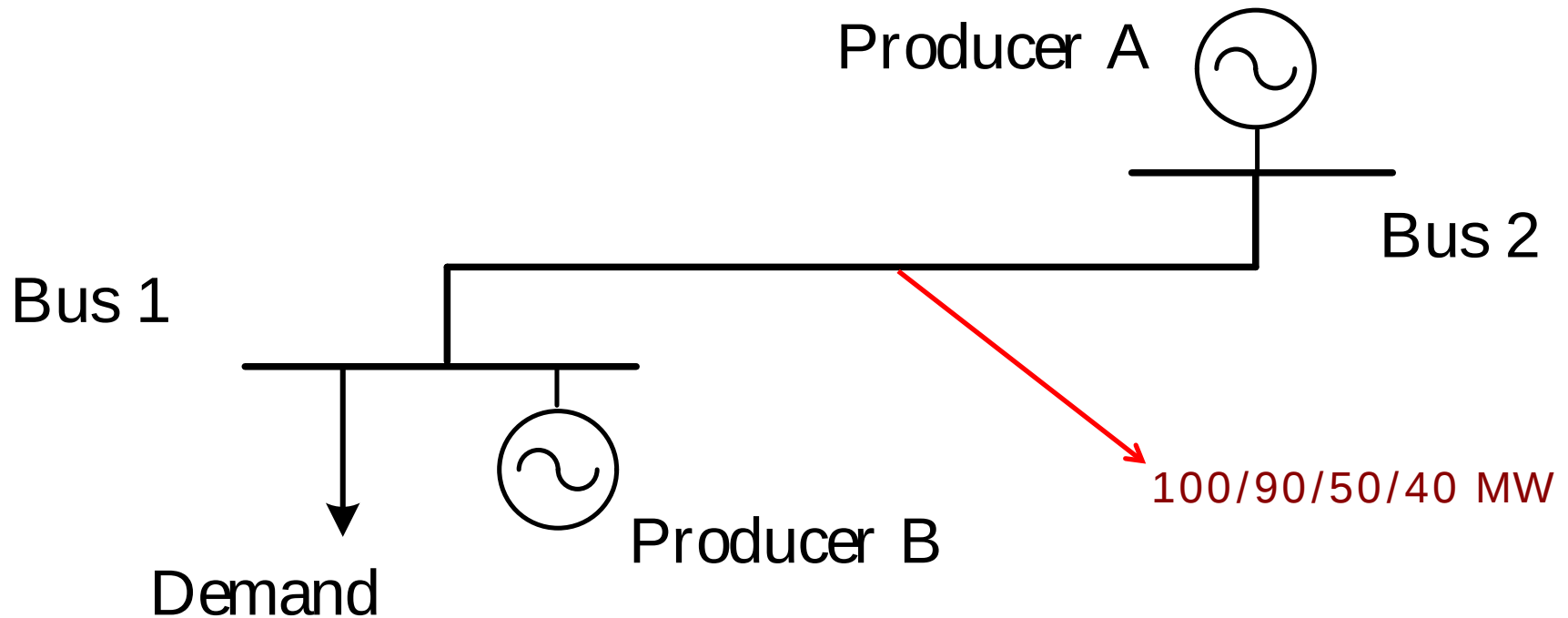
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- Producer B: 100MW & \$30/MWh
- Demand: 130MW  May unexpectedly increase up to 150 MW with a probability of 0.05
- Reserve capacity requirement: 20MW
 - Producer A: free reserve capacity
 - Producer B: \$25/MW

Stochastic market-clearing

(Exercise)

DC load flow model





Thanks for your attention!